The USACE Toolbox of Models for Multi-Dimensional Surface Water-Groundwater Interaction Studies

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Models

"All models are wrong… but some are useful"

George E.P. Box

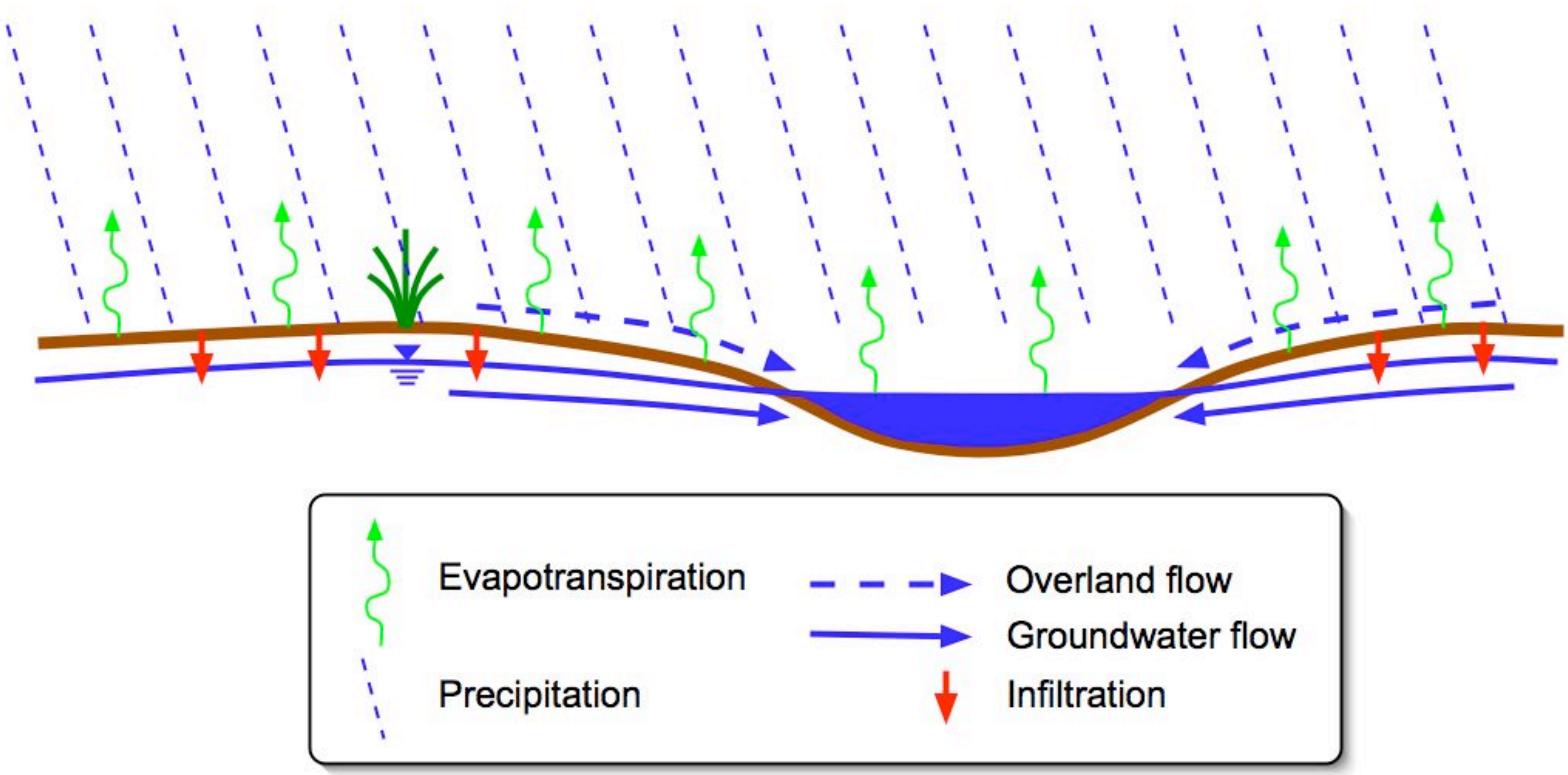
"Make your theory as simple as possible, but no simpler."

A. Einstein

"For every complex question there is a simple and wrong solution."

A. Einstein

Typical Hydrogeologic System with Surface Water Flow Channels



US Army Corps of Engineers

USACE Groundwater-Surface Water Interaction Studies

- Coastal Louisiana
- South Florida/Everglades Restoration

US Army Corps of Engineers

EM 1110-2-1421 ~ Groundwater Hydrology

CECW-EH

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Engineering and Design
GROUNDWATER HYDROLOGY

1. Purpose. The purpose of this manual is to provide guidance to Corps of Engineers personnel who are responsible for groundwater-related projects.

2. Applicability. This manual applies to all USACE Commands having responsibility for design of civil works projects.

3. Distribution Statement. Approved for public release, distribution is unlimited.

FOR THE COMMANDER:

ALBERT J. GENETTI, JR.
Major General, USA
Chief of Staff

US Army Corps
of Engineers

EM 1110-2-1421 ~ Groundwater Hydrology

- Section 6-11, Numerical Modeling of Surface Water and Groundwater Systems:

  "Although mathematically exact, analytic models generally can be applied only to simple one-dimensional problems because of rigid boundary conditions and simplifying assumptions. However, for many studies, analysis of one-dimensional flow is not adequate. Complex systems do not lend themselves to analytical solutions, particularly if the types of stresses acting on the system change with time. Numerical models allow for the approximation of more complex equations and can be applied to more complicated problems without many of the simplifying assumptions required for analytical solutions…" *(emphasis added)*

EM 1110-2-1421 ~ Groundwater Hydrology

- Section 6-11, Numerical Modeling of Surface Water and Groundwater Systems (cont.)

  "…Ideally, a computer model of the surface-water/groundwater regime should be able to simulate three-dimensional variably-saturated flow including: fluctuations in the stage of the surface-water body, infiltration, flow in the unsaturated zone, and flow in the saturated zone. Additionally, simulation of watershed runoff, surface-water flow routing, and evapotranspiration will allow for completeness. However, this is often a complex task, and no matter how powerful the computer or sophisticated the model, simplifying assumptions are necessary." *(emphasis added)*

Challenges in Surface Water-Groundwater Interaction Modeling

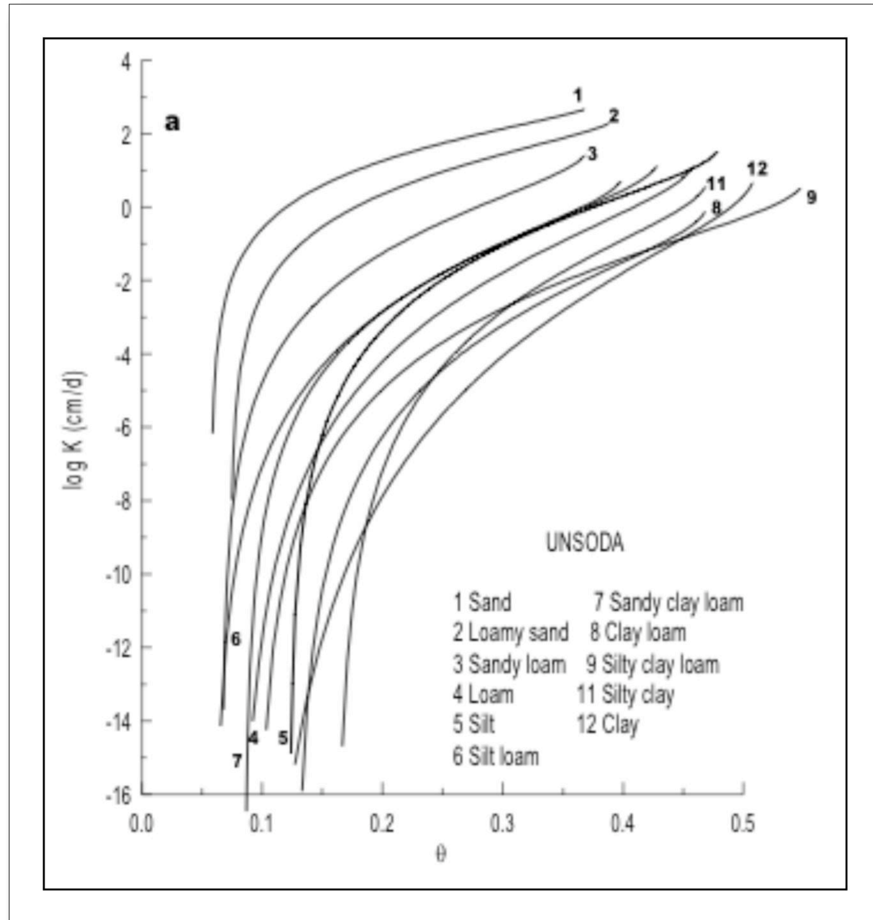
- Disparity in required spatial discretization
- Disparity in required temporal discretization
- Complexity of vadose zone flow computations
  - Richards' Equation (RE)

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial Z}\left(K(\theta)\left(\frac{\partial\psi}{\partial Z}+1\right)\right)$$

The 1D mixed form of the Richards Equation where:
- θ is volumetric soil moisture content (L^3/L^3)
- K(θ) is hydraulic conductivity as a function of θ (L/T)
- ψ is the soil water matric potential (L)
- Z is depth (L)
- t is time (T)

Vadose Zone Challenges

- RE is highly non-linear due to K(θ) relationship
- Can commonly vary over 8+ orders of magnitude for a single soil sample



Appropriate Vertical Discretization for RE

- Downer & Ogden (2004) addressed the appropriate vertical discretization issue on Hortonian and non-Hortonian watersheds
- Vertical resolution on order of 1 cm was needed near soil surface (but not throughout vadose zone) to properly simulate soil fluxes
- Inadequate resolution can lead to several problems:
  - Large (~2000%!) errors in surface fluxes
  - Erroneous conclusions about the sensitivity of physical parameters in the model
  - Physically unrealistic parameter values

Downer, CW and FL Ogden. 2004. Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modelling. Hydrol. Process. ***18****:1-22.*

Infiltration Approximation Alternatives

- Dozens of models available
  - Physically-based
    - Philip, Green & Ampt, Smith-Parlange…
  - Semi-empirical
    - Horton, Holtan, Singh-Yu, Overton…
  - Empirical
    - Kostiakov, Huggins-Monke, Collis-George…
- All are limited by simplifying assumptions, many in the case of high and rising water tables
- None are capable of accurately simulating gravity-driven, unstable infiltration

Mishra, S.K., J.V. Tyagi and V.P. Singh, 2003. Comparison of infiltration models. Hydrological Processes. 17:2629-2652.

System-Wide Water Resources Program (SWWRP)

- 7-year USACE R&D initiative designed to assemble and integrate the diverse components of water resources management
- The ultimate goal is to provide to the Corps, its partners, and stakeholders the overall technological framework and analytical tools to restore and manage water resources and balance human development activities with natural system requirements

System-Wide Water
SWWRP
Resources Program
Water Resources Depot

https://swwrp.usace.army.mil

SWWRP Program Structure

USACE/National Water Resource Needs

Regional Water Management

- Watershed Hydrology Simulation
- Riverine & Estuarine Simulation
- Coastal Simulation
- Water Processes & Assessments

Regional Sediment Management

- River Basin Morphology, Modeling, & Management
- Coastal Morphology, Modeling, & Management
- Sediment Management Methods
- Sediment Processes Studies

Ecosystem Assessment & Management

- Landscape Assessment
- Transport Modeling
- Ecological Modeling
- Ecosystem Response Forecasting
- Ecosystem Processes

Unifying Technologies

- Integrating Frameworks
- Data Management
- Geospatial Applications Development
- Regional Measurement and Monitoring
- Model Integration
- Decision Support and Knowledge Management

Corps Business Lines

SWWRP
Watershed Hydrology Simulation

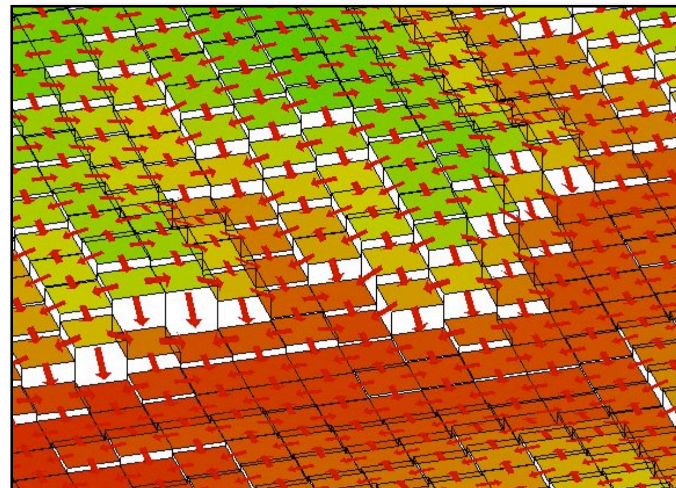
- 5 research areas
  - HMS development
  - GSSHA development
  - Uncertainty/parameter estimation/stochastic simulation tools for system-scale models
  - Regional flood prediction
  - Coupled, multi-dimensional groundwater-surface water interaction simulation

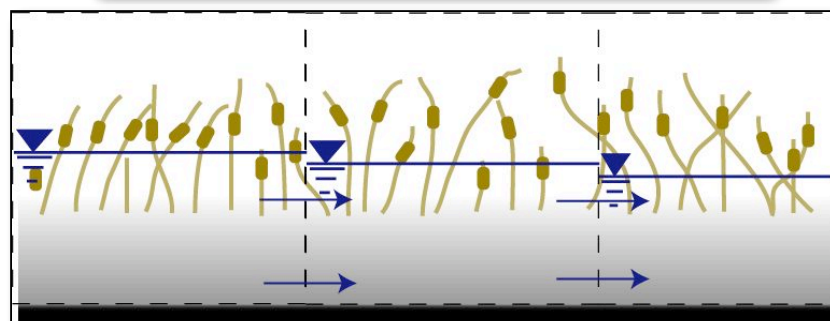
USACE Toolbox of GW-SW Interaction Codes

- Coupled, multi-dimensional, SWWRP-supported GW-SW interaction codes
  - GSSHA
  - WASH123D
  - ADH
- All codes fully integrated and supported in XMS (GMS, SMS, WMS)

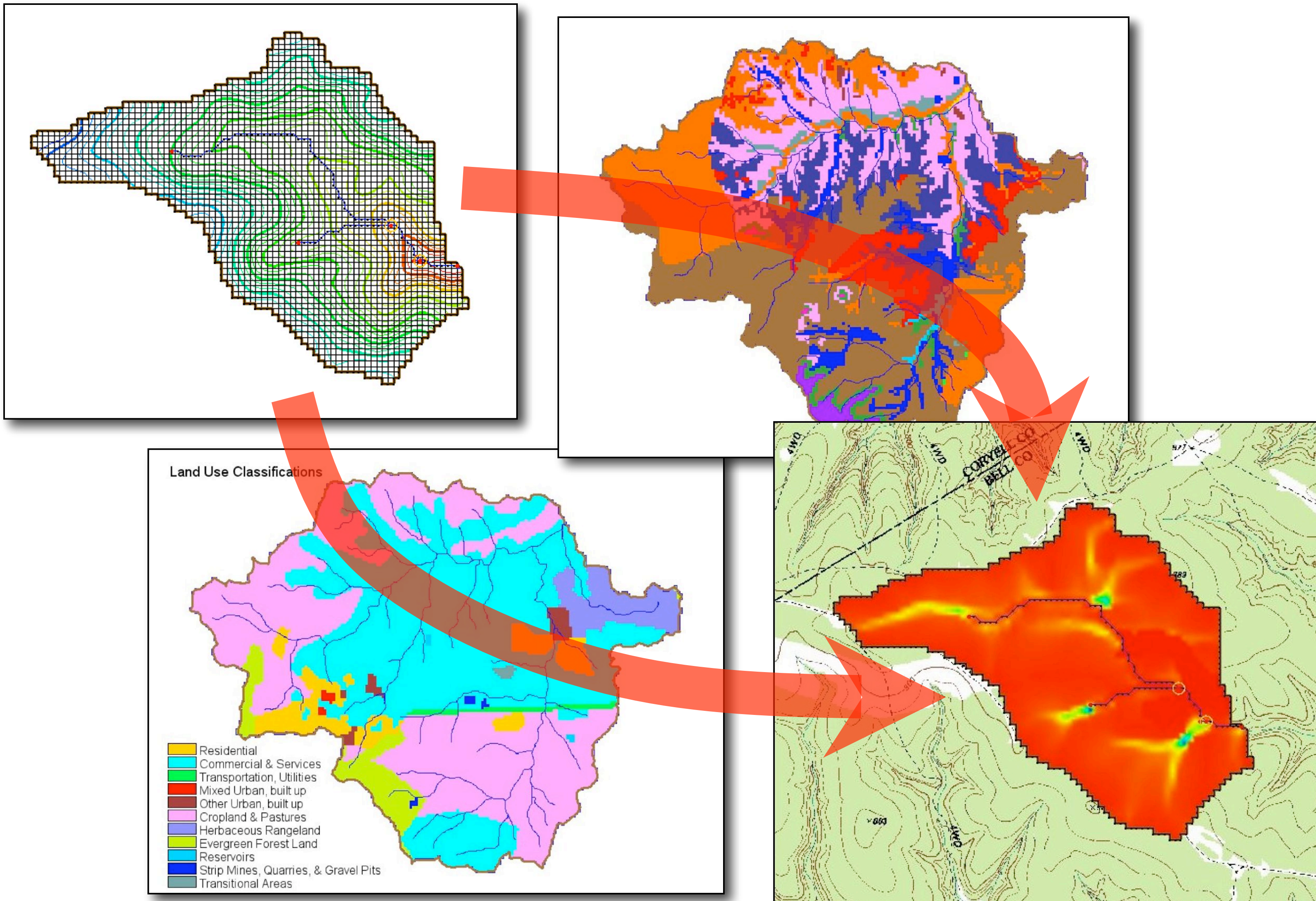
GSSHA

- Distributed, physically-based Gridded Surface Subsurface Hydrological Analysis (GSSHA) model
- Using finite-difference and finite-volume methods, the code simulates:
  - 2D overland flow
  - 1D channel routing
  - 2D saturated groundwater flow
  - Stream/Groundwater Interaction
  - Canopy retention
  - Snowmelt
  - 1D infiltration/ET
  - Storm drainage network flow
  - Wetlands hydrology
  - Sediment transport
  - Tile drains



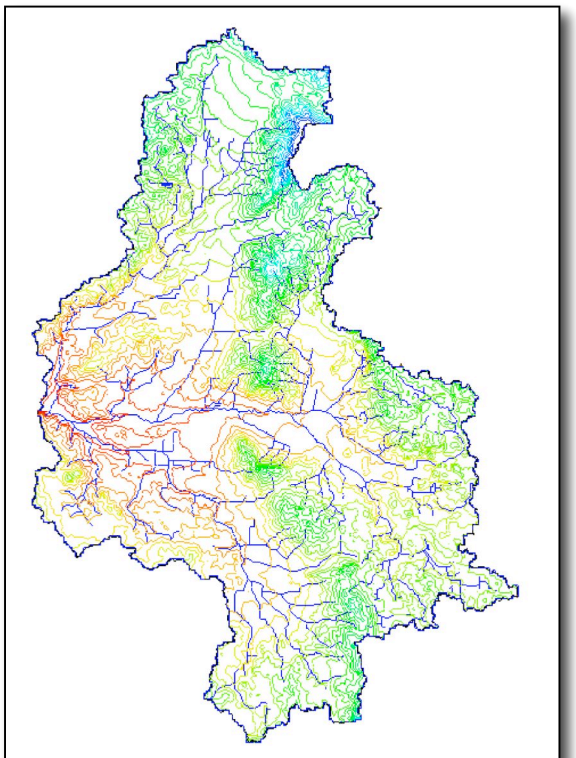


GSSHA

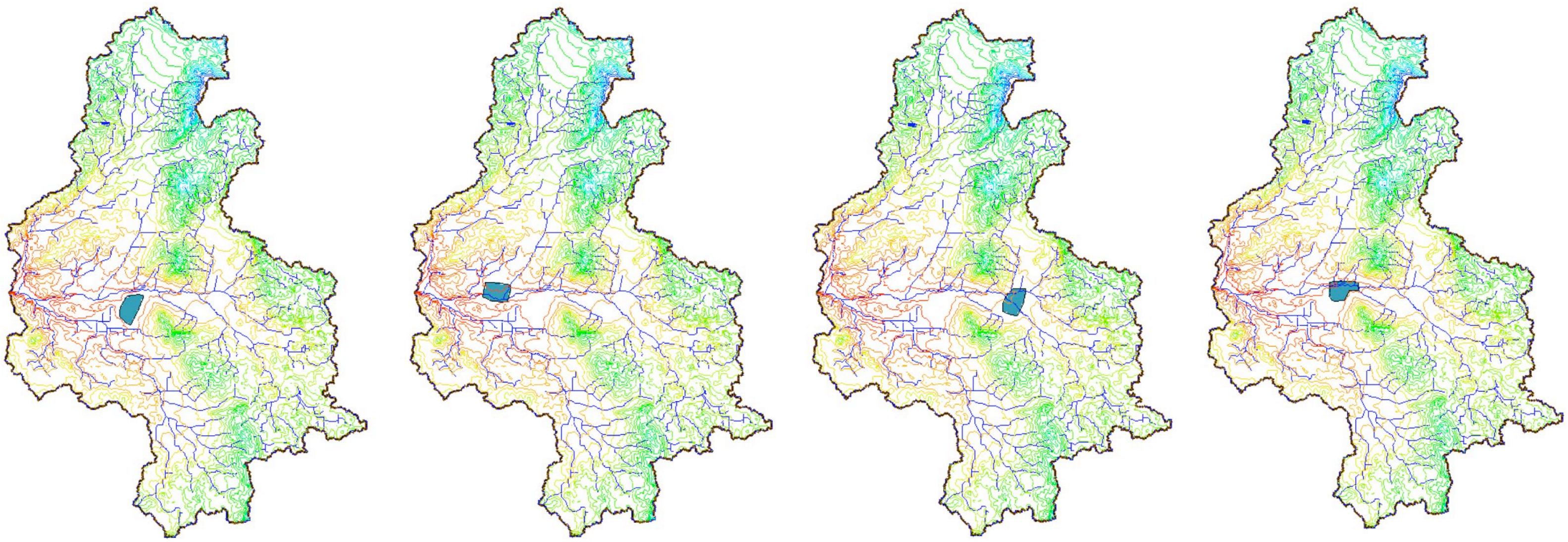

Land Use Classifications
Residential
Commercial & Services
Transportation, Utilities
Mixed Urban, built up
Other Urban, built up
Cropland & Pastures
Herbaceous Rangeland
Evergreen Forest Land
Reservoirs
Strip Mines, Quarries, & Gravel Pits
Transitional Areas

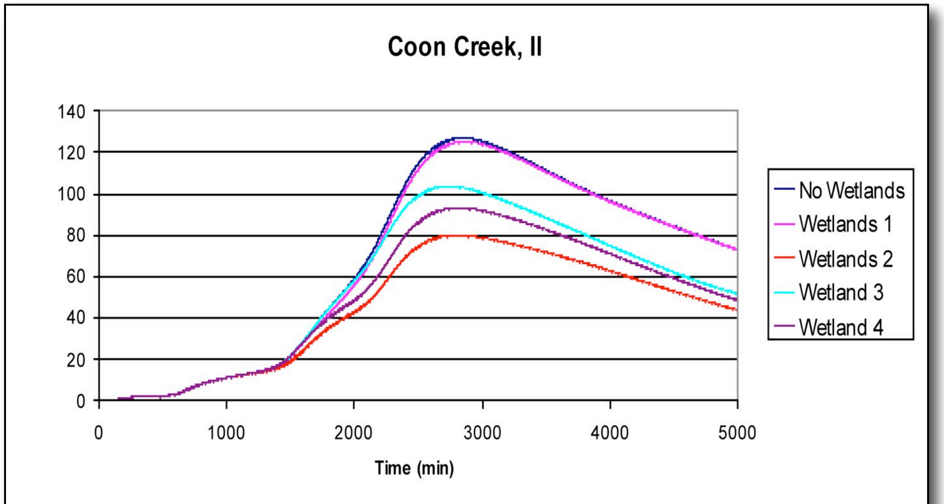
Coon Creek Watershed

- Locate 1600 acre wetland in watershed southwest of Chicago
- Remove tile drains
- Assess impacts of future use



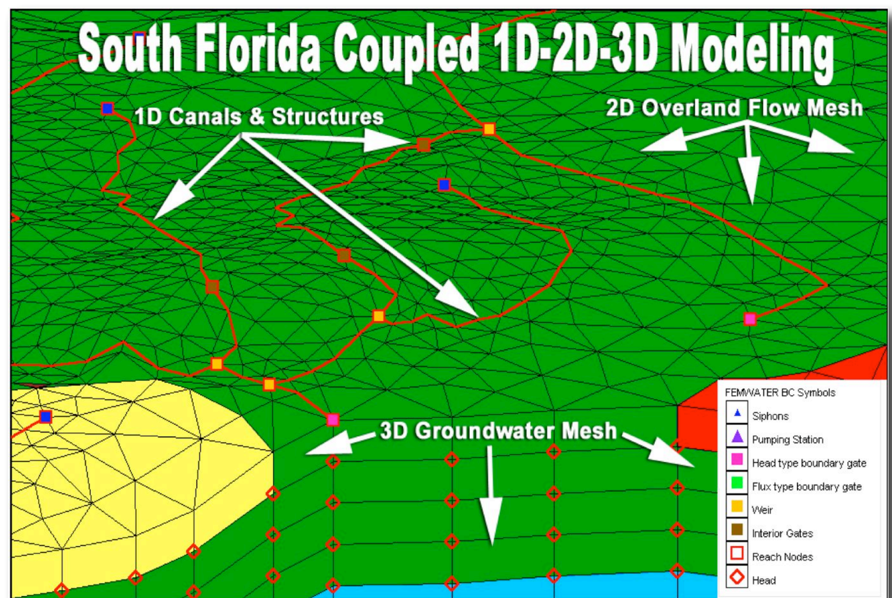
Wetland Placement



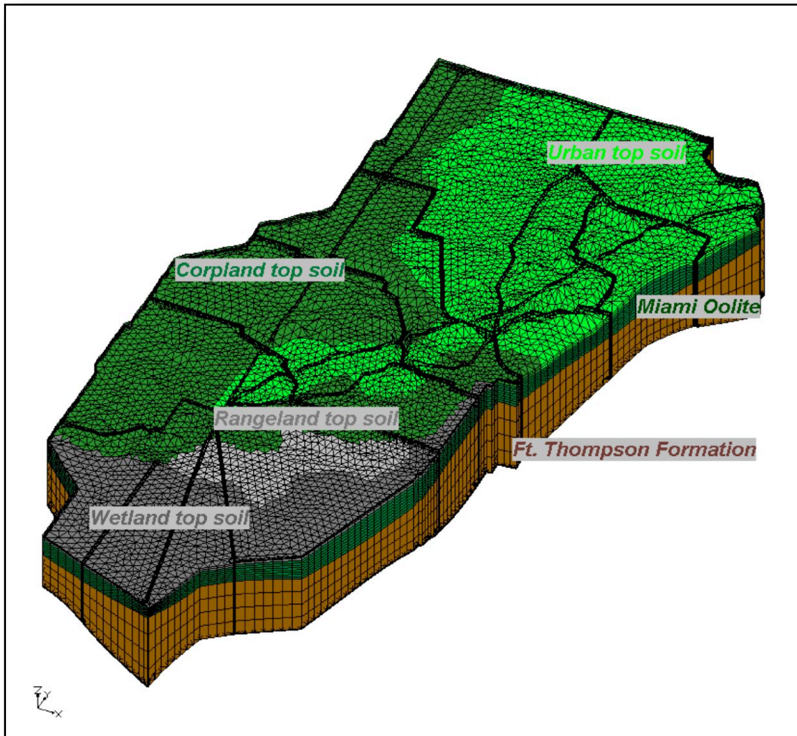


WASH123D

- Water flow and contaminant and sediment transport in <u>WA</u>ter<u>SH</u>ed systems
- First-principle, physics-based finite element watershed model simulating 1D canal, 2D overland and 3D subsurface flow and transport
  - Rigorous coupling
  - Canal operations
  - Parallel



WASH123D

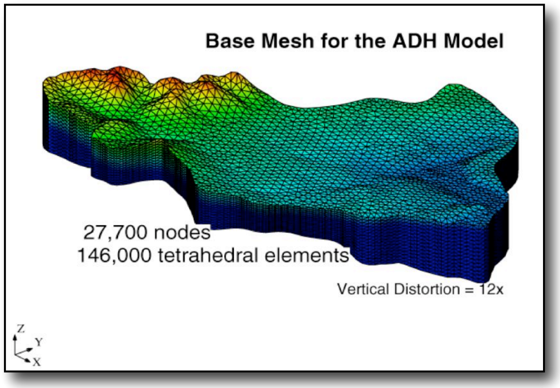


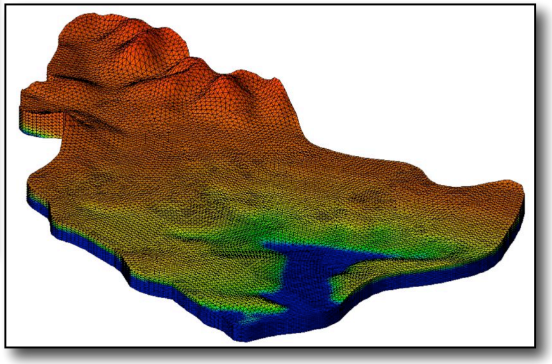
Biscayne Bay
Coastal Wetlands
Mesh

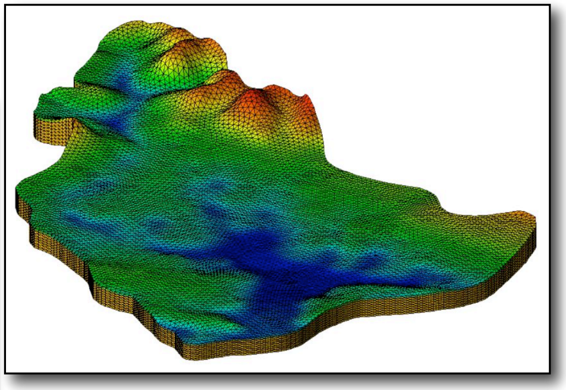
South Florida
Regional Model
Mesh Boundary

ADH

- ADaptive Hydrology/Hydraulics model that simulates flow and transport in coupled surface water - groundwater systems
- Modular, parallel, adaptive finite element simulation of 2D and 3D dynamic wave surface water and 3D Richards' equation groundwater flow and transport





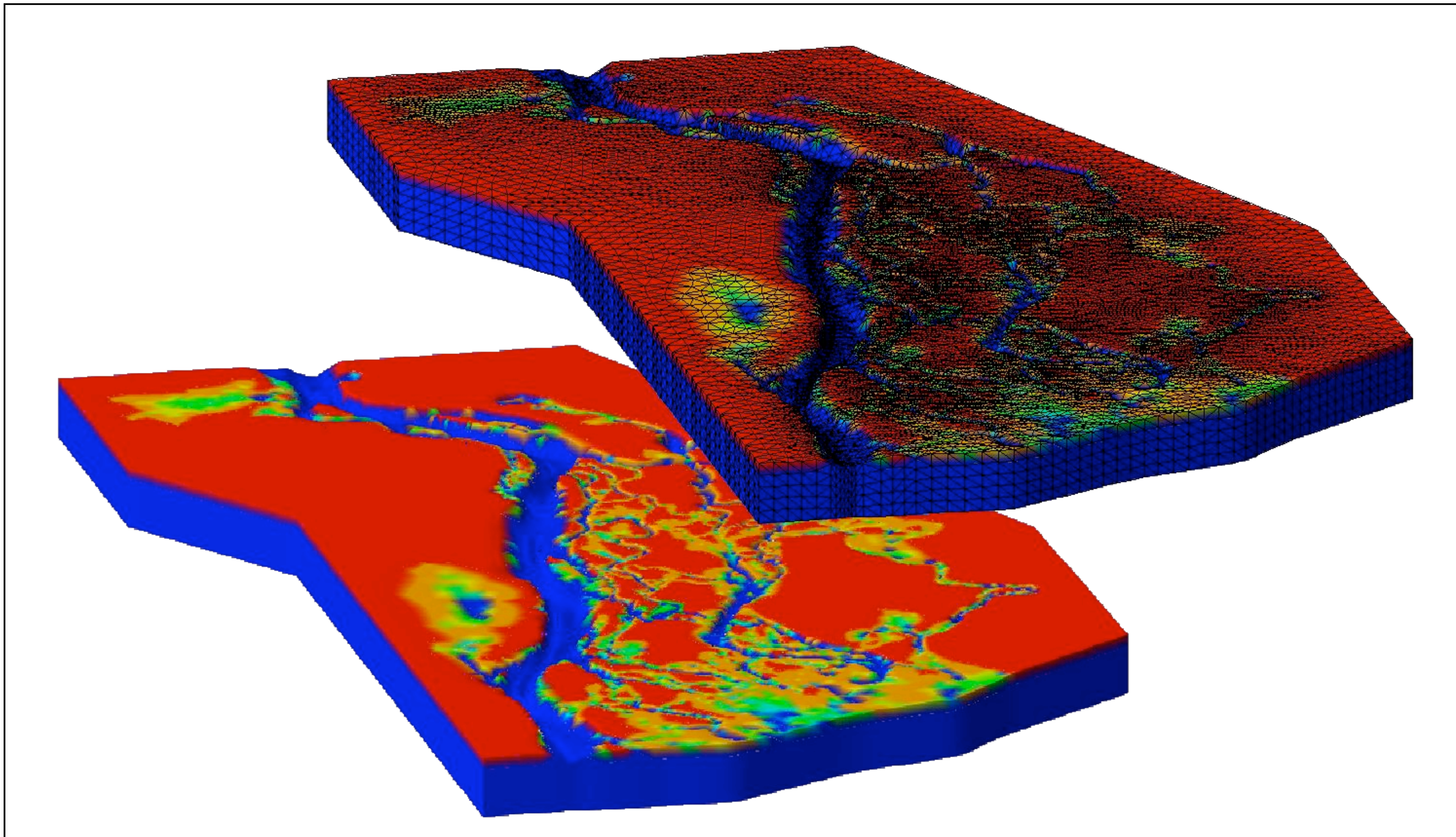


ADH GW-SW Interaction Capabilities

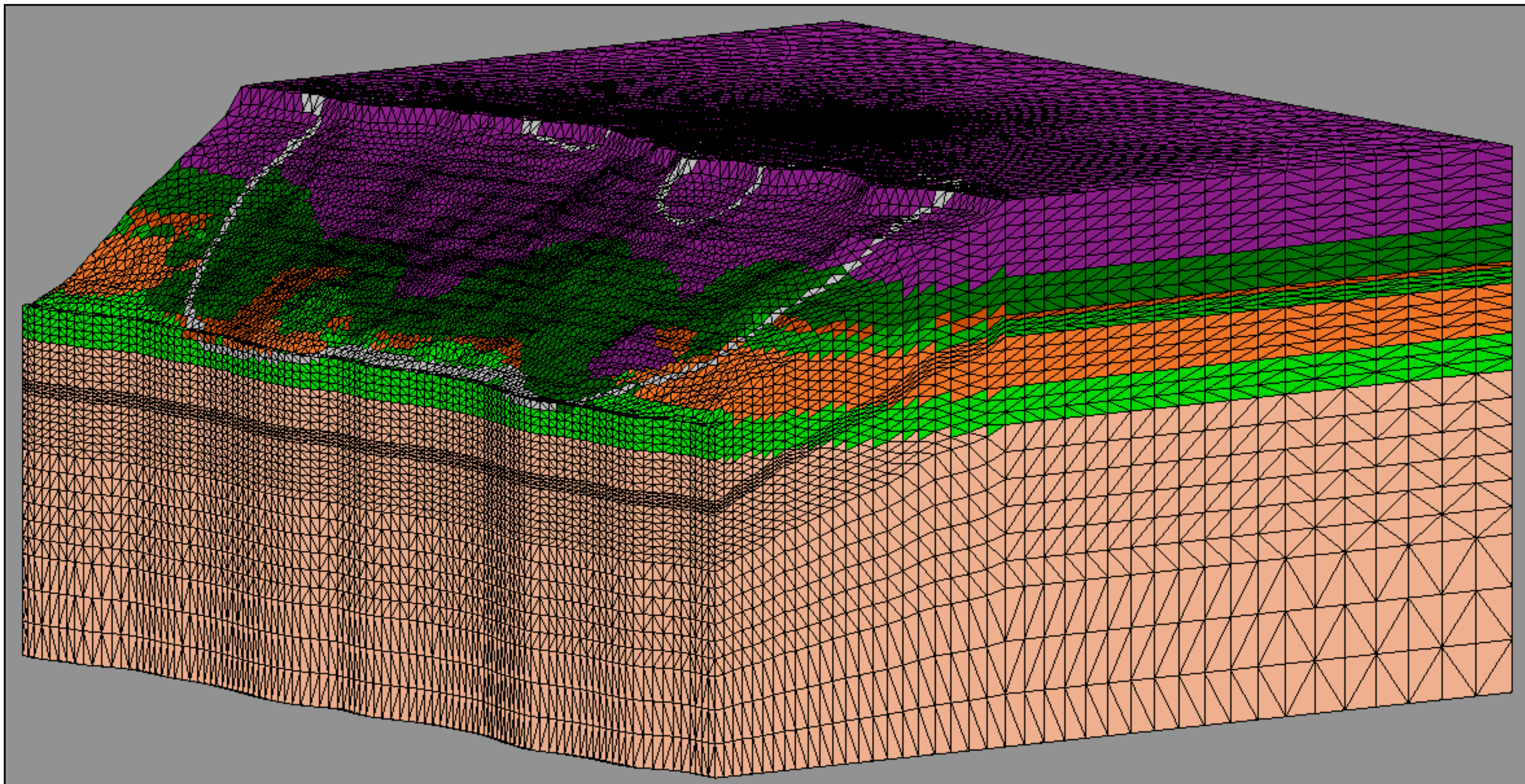
- Coupled 3D groundwater and 2D surface water (diffusive wave and full shallow water) equations
- Flux-based communication avoids switching flux/head boundary
- Dual-valued (SW/GW) nodes on ground surface
- Communication interval is time step
- Separate solves maintain reasonable sizes for the linear systems
- Potential for different time advancement for the hydrologic components
- Designed with parallel processing capability

Pool 8 GW-SW ADH Model

Groundwater Heads and Surface Water Depths



Allegan County Slope Stability Study ~ ADH Model



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Current Status of GW-SW Interaction Toolbox Codes

- GSSHA
  - Fully supported in WMS version 7.x
  - http://chl.erdc.usace.army.mil/software/wms
- WASH123D
  - Fully supported in GMS version 6.0
  - http://chl.erdc.usace.army.mil/software/gms
- ADH
  - Supported in GMS version 6 but full support still under development

SWWRP Deliverables

- Improve infiltration modeling speed by finding physically-based alternatives to Richards' equation
  - Moisture content discretization
  - Two phase (air-water) flow simulation
- Addition of 3D groundwater flow to GSSHA
- Completion of ADH interface development
- Guidance on selection of appropriate physical processes in GW-SW interaction models
- Incorporation of ecological and sediment modeling tools developed in other SWWRP efforts

Conclusions

- Coupled, multi-dimensional GW-SW interaction codes are needed in complex studies (EM 1110-2-1421)
- Currently, several tools exist for performing such studies
  - GSSHA
  - WASH123D
  - ADH
- SWWRP is continuing the development of these tools

Questions? Comments?

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